

INITIAL DEVELOPMENT OF A VARIABLE-FRICTION FLOOR SURFACE

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ABSTRACT

This paper investigates the design of a variable-friction floor device for clinical and rehabilitation applications. Several designs based on rolling elements were proposed and investigated. Coefficients of static friction were measured to compare capabilities of floor tiles made of ball transfer units or covered with PTFE. The measurements showed that while a device based on rolling elements is limited in supported footwear and in simulating heel strike, and can lead to a complex friction-variation system, it can simulate friction coefficients as low as ice.

INTRODUCTION

Falls are a major cause of serious injuries and even deaths. One in three Canadians aged 65 and over will fall at least once every year, causing up to 88% of injuries in this age group [1]. One of the most hazardous conditions is ice where the very top layer is water. A number of human-centred approaches have been used to estimate slipping and falling hazards and risks [2] and to analyze biomechanics [3] and motor patterns [4] when anticipating or walking on slippery floors. One of the challenges of biomechanical studies is reproducing the unexpected nature of real-life slipping accidents [3], which is impeded by the lack of variable-friction floor devices.

In the context of walking, friction is the force resisting the relative motion between the floor surface and a walker's shoe. Reducing friction is usually accomplished by one of the three following methods. One is by using low-friction materials, such as high-density polyethylene (HDPE) or polytetrafluoroethylene (PTFE). Another is by changing dry friction into lubricated friction, that is, placing a lubricant such as oil, water, or grease between the two surfaces. A third way is to change sliding friction into a

much smaller type of rolling friction, with devices such as rolling-element bearings. Friction is commonly quantified with Coulomb's model; examples of coefficients of static friction are 0.04 for PTFE/PTFE contact, 0.02 for ice/steel, or under 0.01 for rolling elements.

Designing a floor device able to generate a wide range of friction coefficients when people walk on it poses two interdependent issues: how to achieve very low friction under load and how to increase friction in a controllable manner. Lubricated friction is not considered here for practical reasons. The very low friction of rolling encouraged us to investigate rolling-based designs of variable-friction floor devices.

1D VARIABLE-FRICTION FLOOR TILE

Rolling objects are frequently used for transport, in particular for moving heavy loads efficiently. A common example is the roller conveyor systems used in material handling and packaging industries. Their capability to provide both very low friction under the weight of a human and a relatively simple way to vary their apparent friction make them a good candidate for a variable-friction floor surface. Indeed, rollers, as 1D-rotating devices, can be borne by bearings on other surfaces than the one in contact with the load. For example, rollers are usually borne by ball bearings located inside, on the sides. Hence, the external surface of rollers can be in contact with both feet above and a braking mechanism underneath.

To ensure a certain spatial resolution in the friction simulation, an array of sets of rollers is necessary, where each set forms an independent variable-friction floor tile. Figure 1 illustrates the design of such a tile, consisting of thirteen $\varnothing 2.2 \times 25$ cm standard conveyor rollers each separated by a 0.8 mm gap. The frame that bears the rollers' shafts is mounted on four load cells that are set under each corner so as

to measure normal forces; a load cell on each side allows measurement of tangential forces. The measure of foot-applied forces can be used for biomechanical analyses but also as inputs for closed-loop control of the friction.

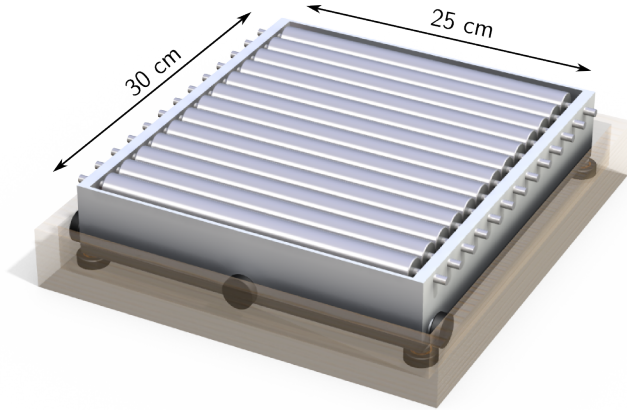


Figure 1: CAD view of a 1D variable-friction floor tile made of conveyor rollers

The variation of friction is realized by a braking mechanism under the rollers. Figure 2 shows an example design in which a brake lining **a** is pressed against rollers **b** above. A lever-arm system is used to apply sufficient force on the brake lining. The plate **c** hinges on the axis **d** and compresses the foam insert **e**, which behaves like an angular spring between the plate and the lining. The axis of rotation is both in the tangent plane of the rollers and in the upper plane of the lining. In this way, the contact surface between the rollers and the lining is distributed over the entire width of the lining and, assuming that the foam has a linear stiffness curve, the force applied by the brake lining on the rollers is the same along the width of the lining. This helps distribute the wear and, as a result, maintains the friction properties of the device over time.

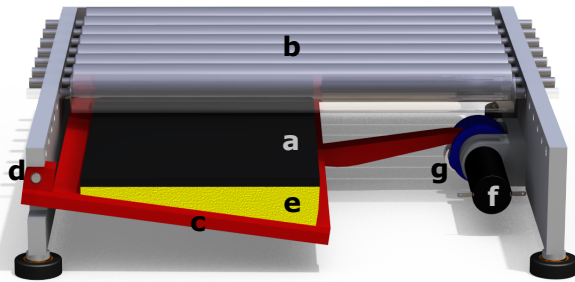


Figure 2: Overview of the braking mechanism

Actuation of the brake is achieved with a conventional $\varnothing 22$ mm DC gear motor **f** driving an off-centre bearing **g** that moves the arm of the plate **c**. As can be seen in Figure 3, the maximal braking force is achieved when the eccentric **g** is at the top of its circular trajectory, which corresponds to very little torque for the motor since the load at this position is borne by the hinge of the eccentric disk. This design results in a compact, simple, and relatively low-cost solution.

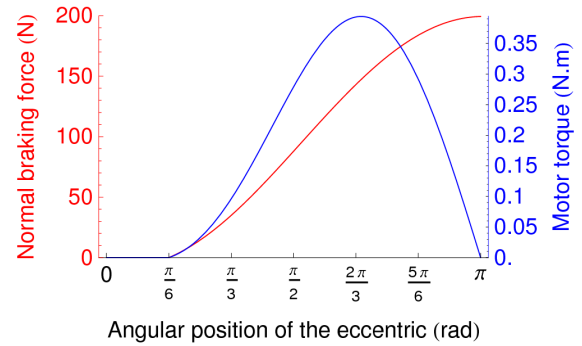


Figure 3: Braking force applied on the rollers and associated motor torque, according to the angular position of the eccentric

Limitations

Although this novel brake mechanism could be effective for altering levels of friction, it suffers from several issues that make it ill-suited for applications in mobility and biomechanics studies. First, the friction variation is restricted to one dimension; in other words, the friction display is *anisotropic*, whereas slippery floors are usually equally slippery in all directions. This difference is likely to induce a different gait from that used on an equally slippery floor. Nevertheless, cases exist where friction anisotropy can be a desirable feature, for example, to simulate the effect of a roller or ice skate.

A second issue relates to the floor shape. Rollers form an *uneven surface* that does not simulate natural floors and would have significant perceptual consequences, mainly if the walker is barefoot and to a lesser extent with shoes. Adding a belt around the rollers may reduce this issue to a certain degree, as the junctions between tiles would nevertheless remain uneven. However, this could significantly impact the fidelity of the friction simulation since it would increase the inertia of moving elements under the foot, as all the belt and rollers would

have to move simultaneously. Another way to flatten the surface is to decrease the roller diameter. Custom rollers using needle roller bearings could lower the diameter to 10 mm.

Another potential issue related to the use of rolling elements is the *vibrotactile noise* emitted by the rollers when turning, which could have perceptual consequences and influence balance control [5]. It could also interfere with vibrotactile actuation if the latter was implemented in the system, as in our previous work [6].

A fourth concern is the *visibility* of the rollers. This provides a visible cue of friction anisotropy and, as a result, is likely to influence people to adjust their gait and locomotion strategies [3]. However, the rollers could be covered with a suitable paint and concealed with video projection techniques.

In summary, the design presented here raises potential issues with respect to several modalities: kinesthetic (friction anisotropy), tactile (shape and vibrotactile), and visual. While the tactile and visual issues can be compensated to a certain extent, the friction anisotropy remains a core limitation of a roller-based design. This led us to investigate the design of an omnidirectional variable-friction device.

2D VARIABLE-FRICTION FLOOR DEVICE

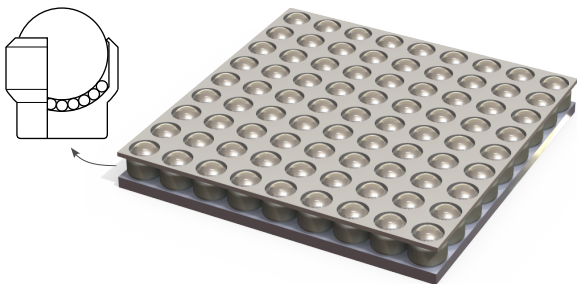


Figure 4: CAD view of an omnidirectional low-friction floor tile, made of ball transfer units

One way to vary friction in both horizontal directions is to use omnidirectional rolling devices, such as ball transfer units (BTUs). Their principle is identical to that of a trackball. As illustrated in Figure 4, a BTU involves a large load-bearing ball supported by many small balls encapsulated in a hemispherical cup. They are commonly used in an array to move objects with minimum effort in any direction, e.g., in cargo and baggage handling applications.

However, unlike 1D-rotating devices such as rollers, the large ball in BTUs is borne on the same surface as the one in contact with the load. This precludes the design of a braking mechanism that is in contact with the ball from underneath, as with rollers.

Different types of BTUs exist according to the fixing method. The appropriate type for our purpose should minimize the outside diameter of the frame compared to the ball size, in order to maximize the array density of units and reduce the uneven-surface issue. These factors suggest the use of bolt or glide¹ unit. This type of units is simple and inexpensive, and its large ball exposure can be advantageous in the design of a braking mechanism. Commercial glide units contain a $\varnothing 25$ mm ball, allowing for construction of an array of 81 units on a 30 x 30 cm tile (see Figure 4) or of 99 units in a hexagonal arrangement. In order to avoid jamming at heel strike, a cover plate above the BTUs' frames would flatten the surface, so that the balls protrude only 2 mm out of the plate.

The friction variation of a BTU-based floor tile could be accomplished in two different ways. First, braking friction could be applied by pressing a rubbing element against each ball, either on its exposed part or on the side, through a hole drilled in the frame of the BTUs. Both options present severe constraints due to the very limited space available for such elements. The second method, raising braking pins between the BTUs that rub against the shoe, may be more reliable, as this does not require any contact with the balls themselves. Different levels of friction could thus be obtained by controlling the number, the size, the height, and/or the material of the raised pins.

This method of friction variation could be implemented in another type of design, without BTUs but with low-friction materials instead. However, BTUs are expected to provide less friction. To verify this, we constructed two prototypes of slippery tiles, one with BTUs (see Figure 5) and another covered with PTFE (see Figure 6). We then compared their coefficients of static friction μ , calculated from empirical measurements of the friction angle φ such as $\mu = \tan \varphi$, as measured by the apparatus illustrated in Figure 6. The tile **a** was tilted by a lin-

1 <http://www.skf.com/files/600570.pdf>

ear actuator **b** (D-Box Odyssey). Its orientation and the movement of shoes were measured by motion capture (OptiTrack) on four people of weight between 50 and 80 kg. The shoes were covered with PTFE sheets for the PTFE tile and with aluminum plates for the BTU tile, as discussed below.

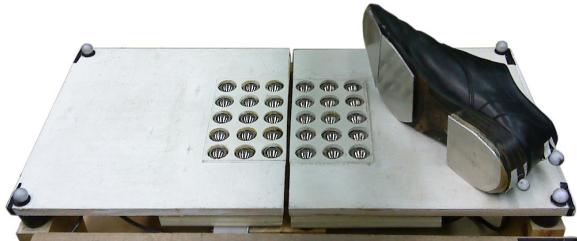


Figure 5: Prototype of slippery tiles with BTUs, made from the vibrotactile floor tiles described in reference [6]

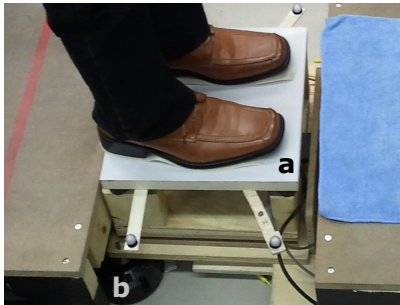


Figure 6: Setup for measuring friction angles

Coefficients of 0.11 ± 0.01 and 0.025 ± 0.005 were measured for the PTFE and BTU tiles, respectively. Although BTUs provide a lower coefficient of static friction, close that of ice, they present some important limitations.

Limitations using BTUs

The spherical surface of BTUs creates a *high contact pressure* between the balls and the walker, which deforms the sole of the foot or the shoe, in particular with soft soles. This can result in the sole, whether barefoot or rubber, contacting the cover plate, which in turn produces friction during walking.

Another constraint, closely related to the issue of uneven surface discussed above, is the space between the BTUs due to their frame. This prevents simulation of a realistic heel strike if the foot is highly inclined, such as during long strides. This limitation could be reduced with a denser array of units and a rounded heel edge. Smaller commercial BTUs, known as miniature BTUs, contain a $\varnothing 5$ mm

ball, but their frame is larger compared to that of glide units. To avoid the heel contacting the frame between the balls, it would need to be rounded sufficiently.

Visibility of balls is harder to compensate than rollers. Steel balls are reflective and cannot be covered with paint, while nonreflecting balls made out of nylon cannot bear sufficient load. Nevertheless, if the entire floor consists of variable-friction BTU tiles, slippery conditions cannot be guessed solely by vision.

CONCLUSION

We proposed and discussed several designs of rolling-based variable-friction floor devices. Ball transfer units allow friction coefficients as low as that of ice but impose some limitations on footwear and for simulating heel strike. Future work includes investigation of another promising approach to vary friction by combining low- and high-friction surfaces in a controllable manner.

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